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Research paper

Prospects for producing liquid wood-based biofuels and impacts in the wood using sectors in Europe

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ABSTRACT

Rapid decarbonisation of the transport sector calls for increased use of biofuels. Part of the increase may be covered by fuels produced from logging residues, wood chips and round wood. This article addresses the economic potential and possible impacts of increased production of such wood based biofuels on the forest industries and production of wood based heat and power in the European Economic Area. A global model for the markets and trade of forest biomass and products, the EFI-GTM was applied for the analysis. The results indicate, firstly, that policy choices will have strong impacts on the allocation of biomass use between heat and power production and the production of liquid biofuels. Hence, the policy makers must have very clear goal setting for the preferred ways to solve the shift from the fossil fuel based energy system to a less carbon intensive one. Nevertheless, because large investments in biofuel production take time to plan and construct, and because the annual forest growth exceeds the harvests of wood in various parts of Europe, there is time to adjust the policies to control the market development. Secondly, even assuming the goal of limiting the global warming to 2 °C, the European forest industry production is projected to be rather little affected by the increased competition for biomass with the energy sector. This is because the rivalling regions are facing similar biomass demand challenges. Also, the relatively abundant wood biomass resources in Europe help the European forest industry to maintain its market shares.

1. Introduction

The Directive 2009/28/EC on renewable energy sources [1] set a 10% mandatory target for a share of renewable energy in the transport sector in the EU by 2020. Various measures, including subsidies and obligations to blend biofuels into conventional petrol and diesel fuels have been implemented by the member states in order to achieve that goal [2]. That has led to an increase in the share of biofuels in transport fuels in the EU28 to 4.2% in 2015 [3]. Yet, the sector is still heavily dependent on fossil fuels. The need for immediate action to decarbonize the transport sector that consumes one third of the final energy in the EU28 [3] paves the ground for a further increase in the use of biofuels. They can be used in existing vehicle stock under existing infrastructure [4]. Furthermore, the biofuels are practically the only available renewable energy source, when it comes to aviation, heavy duty road vehicles, and marine transports.

Although the majority of biofuels is currently and may also in the future be made from non-lignocellulosic biomass, it is expected there will be increased demand for biofuels made of woody biomass too. The EU's Indirect Land Use Change Directive [5] establishes a limiting quota for first generation biofuels and recently, the European Commission proposed a minimum share of 3.6% for advanced biofuels in transport by 2030 [6]. As one option, such fuels can be made of wood. The 3.6% share would require annually 48–62 million tonnes of woody feedstock without additional hydrogen input in production process and 16–24 million tonnes with it [7]. The possible increased use of wood in the production of liquid biofuels is expected to increase competition over biomass and thereby wood prices. That might force some of the other users of wood, for instance heat and power plants, to seek for alternative fuels or technical solutions [8–10].

Only few studies consider the market development and impacts of wood-based biofuels production separately from the biofuels made from other biomass types, or wood based biofuels production separately from all energy wood use. Lauri et al. [11] look at the impacts of increased aggregated demand for wood energy (biofuels + heat and power) on the forest sector and conclude that the global forest industry production is rather insensitive to increased wood demand in the energy sector even if bioenergy was to be produced in a scale required for the 2° C climate goal. They project that 5000 $hm^3\ y^{-1}$ of round wood and forest chips would be used for energy globally by 2100 in such case.

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Studies focusing on Norway [10] and Finland [8] demonstrate that large-scale investments on second-generation wood-based biofuels would increase biomass prices and reduce bioheat generation. Also the prices of sawmill chips could increase following such investments despite the abundant supply of biomass in the Nordic countries [12]. That can generate a modest increase in sawnwood production [11,12].

This study aims to examine (i) how alternative combinations of biofuel and biomass prices affect the production potential of liquid biofuels made of wood and allocation of wood biomass between biofuels and heat and power production in the European Economic Area, and (ii) what are the possible impacts that increased biofuel production could cause to the forest sector. The study focuses on bioenergy produced from logging residues, sawmill chips and round wood.

Large uncertainty prevails regarding the future supply and market prices of woody biomass and biofuels made of it. These factors are affected by the consumers' behaviour (e.g. demand for biofuels, heat and power, and forest industry products), by the costs and availability of alternative energy forms, and by the policies (taxation, subsidies, and prices of CO_2 emission allowances, etc.). These issues affect the tightness of competition for biomass between the users and make the investment and operation environment unpredictable. To overcome some of this uncertainty, we consider alternative future markets environments, where we explore the development of wood based biofuels production, allocation of wood feedstock between heat and power production and biofuels, and the impacts of the increased use of wood for energy on the forest industries. In order to create and consistently quantify these market environments, we use a global forest sector model, EFI-GTM [13]. The EFI-GTM model includes the international trade in all main wood biomass and forest industry products. This approach enables us to take into account for the vision that the use of wood based energy is increasing also outside of Europe [11,14,15]. Due to international trade, Europe is not isolated from the global developments.

2. Material and methods

2.1. The global forest sector model, EFI-GTM

The EFI-GTM is a multi-regional and multi-periodic partial equilibrium model of the global forest sector. It integrates forestry, forest industries, final demand for forest industry products and international trade in wood biomass and forest industry products. It includes 57 regions covering the whole world, but the regional disaggregation is most detailed in Europe. Most European countries are modelled as individual regions. The updated version used in this study encompassed about 30 forest industry and energy sector products, 5 round wood and 3 forest chips categories, 4 recycled paper grades, and the by-products of the forest industries.

The partial equilibrium approach implies that the other sectors of the economy than those related to the supply and demand of wood and forest-based products are only considered indirectly. The model finds the competitive market equilibrium prices and market equilibrium quantities of production, consumption and trade for products and regions included. Concerning transport biofuels, we include the trade in wood biomass that can be used in production of biofuels in any region where profitable, but we do not include further trade in biofuels although such trade can take of course place in practise.

The competitive market equilibrium is solved by maximizing the sum of consumers' and producers' surpluses of all regions and products minus the trading costs. The model is solved in a recursive-dynamic fashion by one period at a time, updating the relevant data for the next period in each step. The general model formulation is presented in the Appendix, while more details concerning the functional forms and solving the model can be found from Ref. [13].

2.2. Scenarios considered

We consider two scenario settings A and B described in their own sections in more detail below. In setting A, the focus is to explore the impacts of the increased use of wood-based energy on the forest industry. Setting B focuses on wood-based biofuel production and allocation of wood biomass between biofuel and heat and power producers.

In defining the global demand drivers for the forest industry products in these two settings A and B, we followed the assumptions elaborated within a scenario “Bioinno” in a recent study by Kallio et al. [15]. The regional consumptions per capita of mechanical forest industry products were assumed to be 50% higher than their 2008–2012 averages by 2050. Demand for the printing and writing papers was assumed to decline gradually due ongoing substitution by the electronic media, being globally 18% lower in 2040 than in 2010. Assuming the future textile industries to increasingly favour wood based fabrics, the demand for dissolving and non-paper pulp was assumed to increase rapidly, in particularly after 2025, reaching 55 million tonnes by 2040. For the rest of the final forest industry products, the demand was tied to GDP growth employing the GDP elasticities from the econometric studies and expert estimates. The GDP growths were assumed to follow the IMF's forecast [16] for the regions it was available and then to converge to the OECD's [17] long run forecast by 2030 and stay at that level thereafter. The above assumptions were only used to specify the demand functions over time. The eventual demands projected by the model depend on the markets that are balancing supply and demand.

We also partly capitalized on the energy sector development in Ref. [15], as detailed below and summarized in Table 1. We considered the “Bioinno” scenario to be an interesting reference point for the present analysis because it includes the assumption that the global energy sector adapts to the goal of limiting climatic warming below 2° C. Consequently, the use of biofuels and production of bio-based heat and power increases considerably in Europe and globally. It is of interest to compare the quantities of wood-based heat, power, and biofuels in alternative biofuel and biomass price settings in this study to the quantities projected to be needed for the 2° C goal. Furthermore, because reaching the 2° C climate goal is challenging, we consider it to be somewhat unlikely that wood-based bioenergy would increase even more rapidly than in “Bioinno”. In the EFI-GTM version used in this study, we do not include alternative energy production forms competing with wood-based energy. Hence, it is convenient to use the “Bioinno” quantities as boundaries for wood based heat and power production in the scenarios when we address the biofuel production. In Ref. [15], the projections for the global energy system were made by Lehtilä and Koljonen with the global energy model TIMES-VTT which is based on widely used TIMES modelling framework [18,19]. The model is grounded in microeconomic theory and it mimics forward-looking market behaviour by the market participants in the global energy sector. The model is frequently used to support national energy and climate policy making in Finland [20].

More information on the main data and assumptions used in the modelling can, in addition to what is described below, be found from Refs. [13,15] and from the Appendix.

2.2.1. Setting A: comparing the impacts of varying global demand for wood bioenergy on the forest industry

Here, we compare three scenarios to examine the influence of potential future increases in the global demand for wood in heat, power and biofuel productions on the forest industry in Europe. We calculate two alternative cases to the “Bioinno” scenario [15]. In “Bioinno”, use of woody biomass is growing in all fronts: in the forest industry, in heat and power production, and in production of biofuels. In one alternative, we remove the possibility to increase production of wood-based transport fuels, but assume the heat and power production to increase as in “Bioinno”. In another alternative, we allow no increase in any wood based energy production after 2010, so that the forest industry

Table 1
Summary of the main scenario assumptions regarding the production of wood based biofuels and heat and power (h&p) in the settings A and B.

	Setting A			Setting B
	No increase of wood[a] based energy after 2010	Energy wood use increases in h&p production only	Energy wood use increases in h&p production and biofuels (< 2 °C)	12 combinations of prices that h&p plants can pay for wood at maximum and biofuel prices
Wood demand in h&p plants in 2040				
The EEA	150 TWh[b]	253 TWh[c]	253 TWh[c]	Constrained to be at most 253 TWh
The rest of the world	380 TWh	1067 TWh[c]	1067 TWh[c]	Constrained to be at most 1067 TWh[c]
Production of wood based biofuels in 2040				
The EEA	0	0	104 TWh	Constrained to be at most 1223 TWh[d]
The rest of the world	0	0	1149 TWh	Constrained to be at most 1149 TWh[c]
Price h&p plants can afford to pay for wood	endogenous	endogenous	endogenous	20, 30 or 40 €·MWh^{-1}
Price of liquid biofuel	not relevant	not relevant	Endogenous (median of the regional reference prices given to the model was 69 €·MWh^{-1})	70, 80, 90 or 100 €·MWh^{-1}

[a] Wood refers here to logging residues, sawmill chips and roundwood.
[b] In the EFI-GTM, we assumed that 1 m^3 of wood corresponds roughly to 2 MWh.
[c] Based on the projection of the quantity needed to satisfy the 2 °C climate goal in Ref. [15].
[d] 50% of the transport sector energy demand projected in National Energy Action Plans of the EU member states for 2020.

gets to be the sole user of the growing wood resources.

2.2.2. Setting B: comparing energy wood uses under alternative bioenergy pricing schemes

Here, we examine the supply of biofuels and allocation of wood biomass between biofuels and heat and power production in the EEA under alternative operations environments. We vary the energy sector market assumptions concerning (i) the producer price paid for liquid biofuels and (ii) the maximum price that heat and power producers can pay for wood biomass in order to compete for that with other users. The results will also be reflected against the wood energy quantities of "Bioinno" [15], to assess which market conditions make it possible to achieve the scenario path for "Bioinno" with the 2 °C climate mitigation target.

The price afforded by the heat and power producers to pay for energy wood is varied from 20 € to 40 € per MWh of wood feedstock and the producer prices of liquid biofuels is varied from 70 to 100 € per MWh of fuel. We consider the projected consequences of these alternative price settings but not the drivers or causes behind these prices. They can be interpreted to result from the alternative levels of technical development affecting the position of the producers in the feedstock market or they can result from and encompass various alternative configurations of taxes and subsidies applied to the energy sector. For instance, the price of 40 €·MWh^{-1} for wood corresponds to some 80 €·m^{-3} and can be regarded to be quite high compared to the current wood costs even in many industrial purposes, for instance pulp production. Yet, some existing subsidy systems for biobased electricity already lead to the situation where energy producers can pay relatively high prices for wood. Proskurina et al. [21] report subsidies for the biobased electricity of the magnitude up to 60 €·MWh^{-1} (Denmark), 53 €·MWh^{-1} (Estonia), and 56 €·MWh^{-1} (the United Kingdom), at least for some power plant installations. Even when converted to the feedstock level (e.g. assuming the fuel-to-electricity conversion efficiency of 30% [2]), these subsidies may raise considerably the price that can be paid for wood in power production and have a significant impact on the European wood based sectors [22]. Also, a price set on carbon, for instance in the form of emission allowance price, has impact on the price that heat and power producers can pay for wood.

In the model simulations, we constrained the wood based heat and power production in the EEA and the Rest of the World (hereafter RoW) to be at most in the level of the "Bioinno" [15] production. The wood-based liquid biofuel production in each EEA country was allowed be higher than in "Bioinno", but limited not to raise linearly more than to reach by 2050 the level of 50% of the *total* transport fuel use in 2020 estimated in the National Renewable Energy Action Plans of the EU MSs [23]. This allows a generous increase in European biofuels production. In RoW, we limited the liquid biofuel production not to exceed the "Bioinno" levels. These boundaries summarized in Table 1 were implemented as constraints into the EFI-GTM model.

2.2.3. Assumed available biofuel production technologies

Data on alternative technologies for biofuels production into the EFI-GTM model were formed or directly taken from McKeough and Kurkela [24], Hannula and Kurkela [25] and Hannula [26]. The data are summarized in Table A 1 in Appendix. In the model simulations, the regions chose almost solely a Fischer-Tropsch technology with biomass to biofuel conversion efficiency of 57% due to its more favourable cost structure concerning other inputs than biomass. Because there are no large scale plants making liquid biofuels from forest chips or roundwood in commercial operation, there is uncertainty over the eventual production costs. The alternative schemes for liquid biofuels prices in setting B can also been interpreted to cater for variations in marginal production costs.

3. Results and discussion

3.1. Impacts of increased biofuels production on the forest sector

Let us start by considering the impacts in the EEA related to wood harvests and prices and forest industry production (setting A).

3.1.1. Wood harvests and prices

The large quantities of energy wood (214 hm^3) projected in Ref. [15] to be needed in the EEA in 2040 for going towards the 2° C climate goal can be reached with forest chips and fuelwood as main biomass sources. Still, the European pulpwood harvests increase considerably compared to the case where there would not be any new liquid biofuel production (Fig. 1). The reason is that in the case where large quantities of biomass are used for decarbonising the global transport sector, biofuel production increases globally and not only in the EEA. This reduces considerably the possibilities of the EEA forest industry to import pulpwood from the rest of the world. Consequently, the wood harvests

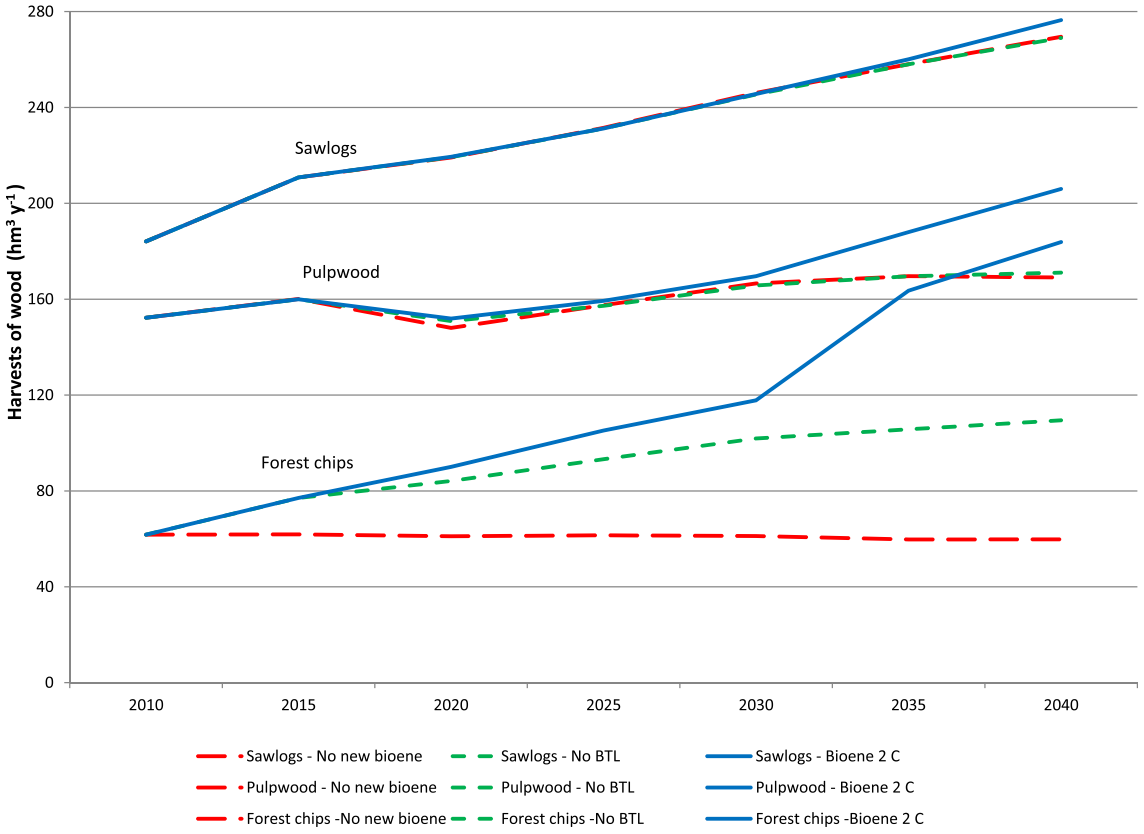

Fig. 1. Projected harvests of sawlogs, pulpwood and forest chips in the EEA when (i) demand for energy wood stays at 2010 level ("Now new bioene"), (ii) wood use increases in heat and power production but no wood based biofuels enter the market ("No BTL"), and (iii) all bioenergy increases contributing to limit climatic warming to 2 °C ("Bioene 2 C").

in the EEA are increased to compensate the cut in imports. In 2040, pulpwood harvests in the EEA are projected to be 20% (35 hm^3) higher in the case where wood-based liquid fuels are produced than in the case where modern energy wood only goes to heat and power production in increasing amounts. This also affects the prices of pulpwood and forest chips (Fig. 2) that are over 40% higher in the case where wood-based liquid biofuels enter the market than without them.

The price and demand increases for pulpwood and wood used for energy do not bring an important raise in the sawlog harvests in the EEA (Fig. 1), although that could be expected noting that the increasing value of sawmill chips could improve the profitability of sawnwood production and thus increase the sawlog demand. The difference in the sawlog harvests between the scenarios is about 7 hm^3 (less than 3%) in 2040 for the whole EEA region. Even this modest change is mainly due to reduced net imports of logs to the EEA, mostly hardwood, which calls for increased domestic harvests. The EU sawnwood production is not profiting more from the situation, because being a global phenomenon, the increase in the use of energy wood does not bring any particular advantage to the producers of sawnwood in the EEA.

If wood based bioenergy production remained in the 2010 level, prices of forest chips would decline in the long run (Fig. 2), because their supply would be higher due to increasing roundwood harvests from which they come as a side-product and because increasing amounts of household fuelwood could be used for more efficient modern energy relieving the pressure to harvest forest chips for that. Instead, pulpwood prices tend to be rising in any case due to increased forest industry production. Fig. 2 also shows that setting the biofuel production to match the biomass needed for meeting the 2 °C climate goal would cause high pulpwood price increases after 2030 in the EEA because of the consequent changes in world trade.

3.1.2. The forest industry

In the scenarios with increased wood based energy production for the 2 °C climate goal, this increase takes place globally. In such setting, the operating environment of the forest industries is affected everywhere and not only in the EEA. Therefore the forest industry production is not projected to be changed much in the EEA across the cases (Fig. 3).

The results also show that the impacts of bioenergy on the forest industries are not always obvious. The chemical pulp production in the EEA is projected to be 2–4% higher during 2025–2030 in the case where both wood based liquid biofuels and wood-based heat and power production are increased globally than in the cases with less bioenergy, although one would expect the pulp production to decline due to stronger competition for biomass. At the same time, the global total chemical pulp consumption is projected to be marginally lower than in the other cases. This is because the investments in new capacity in RoW take place more slowly in the case where there is strong competition over biomass between the energy sector and the forest industry. The forest resources in the EEA allow for increase in wood-based bioenergy production, while the forest industry production is somewhat stagnant due to mature product markets. Nevertheless, by 2040, the EEA pulp production is projected to be some 5% lower with biofuels than without them. The results indicate that the available forest resources in the EEA may bring some advantage to the region's forest industry in the next decades by improving its possibilities for meeting the tightening global competition in the longer run.

3.2. Comparing the market outcomes under alternative biofuel pricing schemes

Let us now look more closely at the production volumes of wood based biofuels in the EEA and the allocation of wood between liquid biofuels and heat and power under alternative pricing schemes (setting

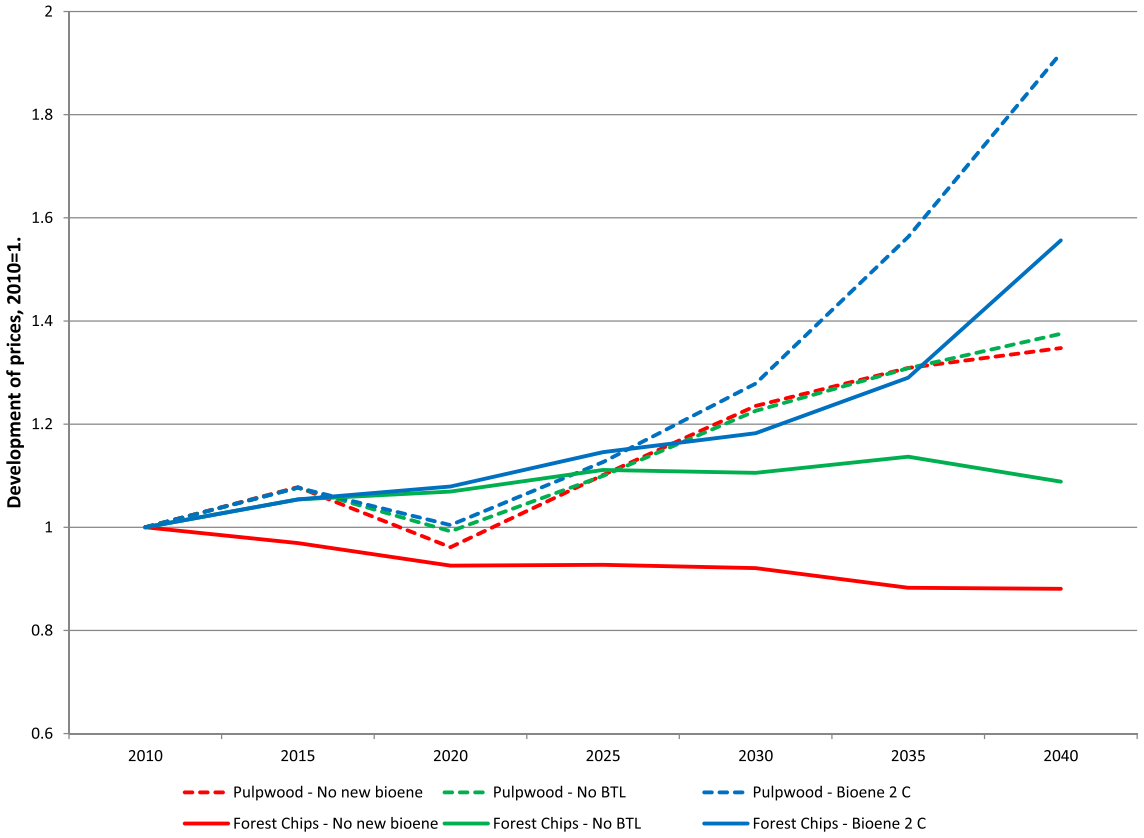

Fig. 2. Projected development of average market equilibrium prices in the EEA for softwood pulpwood and forest chips with 2010 = 1.0 when (i) bioenergy demand stays at 2010 level ("No new bioene"), (ii) wood use increases in heat and power production but no wood based biofuels enter the market ("No BTL"), and (iii) all bioenergy increases contributing to limit climatic warming to 2 °C ("Bioene 2 C").

B) as displayed in Figs. 4 and 5.

Across the pricing combinations considered, the highest quantity of liquid biofuels in the EEA can be expected under the setting where heat and power plants are able to pay at most 20 €·MWh^{-1} for wood and mill gate price is 100 €·MWh^{-1} for biofuels (Fig. 4a). Such combination leads to the production of 800 TWh of transport biofuels made out of wood in the EEA in 2040. Furthermore, no wood would be used for modern heat and power production after 2025, as then the price for energy wood is driven above the level of 20 €·MWh^{-1}. The average price of energy wood in the EEA exceeds 40 €·MWh^{-1} by 2035 and continues to increase after that due to increased competition for wood globally.

When we decrease the assumed biofuel price to 70 €·MWh^{-1} and let the heat and power plants pay at most 20 €·MWh^{-1} for wood (Fig. 4d), the quantities of wood used in heat and power plants are projected to decline to be only one third of the quantity in 2010 by 2040, whereas liquid biofuel production raises to about 160 TWh in the EEA. The projected average price for energy wood biomass remains below 25 €·MWh^{-1} in the EEA in this case. After 2020, the liquid biofuels production only increases in Nordic countries and in Eastern Europe, where biomass availability and costs make that possible.

At the price of 20 €·MWh^{-1}, the supply of energy wood is rather limited and it depends on the profitability of the alternative end uses where the supply is directed. Instead, if heat and power producers can afford to pay 30 €·MWh^{-1} or more, they can source considerably more wood (Figs. 4 and 5) despite the competition coming from the biofuel producers. It is to be noted, however, that at the regional level, also the local transport costs for forest biomass would affect the use of biomass [10]. The need for transporting the feedstock can make it possible for small heat producers to buy smaller quantities locally, as large liquid biofuel producers need to add transport costs both for feedstock and the end products.

In Ref. [15] it was projected that in order to meet the 2 °C climate goal the quantity of energy wood used in modern heat and power production in the EEA would need to increase from 150 TWh in 2010 to up to 250 TWh in 2030–2040. Fig. 5a–d shows that such energy wood quantities in modern heat and power productions are fully obtained in the cases where heat and power plants can afford to pay up to 40 €·MWh^{-1} for wood and where biofuel producers get 70 to 80 €·MWh^{-1} of their output. With higher biofuel prices of 90 €·MWh^{-1} or 100 €·MWh^{-1} examined in this setting, such 2 °C quantities for heat and power can only be obtained before 2030. After that the increased biofuel production drives the average price of energy wood to the level above 40 €·MWh^{-1}.

In the"Bioinno" scenario [15], the quantity of energy wood projected to be needed for liquid biofuel production in the EEA to match the 2 °C climate goal was roughly 100 TWh by 2040. Such production in 2040 is projected to be obtained for instance if heat and power producers can pay 30 €·MWh^{-1} for their wood feedstock and where biofuel producers get 70 €·MWh^{-1} for their output (Fig. 5). At several other settings with higher biofuel price or lower ability for heat and power producers to pay for biomass, the EEA production of liquid biofuels are projected to be considerably higher than 100 TWh.

Even in the cases where the heat and power plants are assumed to be able to pay up to 40 €·MWh^{-1} for wood biomass and the biofuel prices are not assumed to be very high, the liquid biofuel production is supported by path dependency. In the early years before 2030, wood biomass price is projected to be well below 40 €·MWh^{-1}, and much of the investment activities in biorefineries take place then (Fig. 5a–d). As the investments are irreversible the existing facilities will be kept in use even despite their poor profitability later on.

It is far from obvious that the most sumptuous biofuel quantities projected above could materialize even if shown feasible in the model

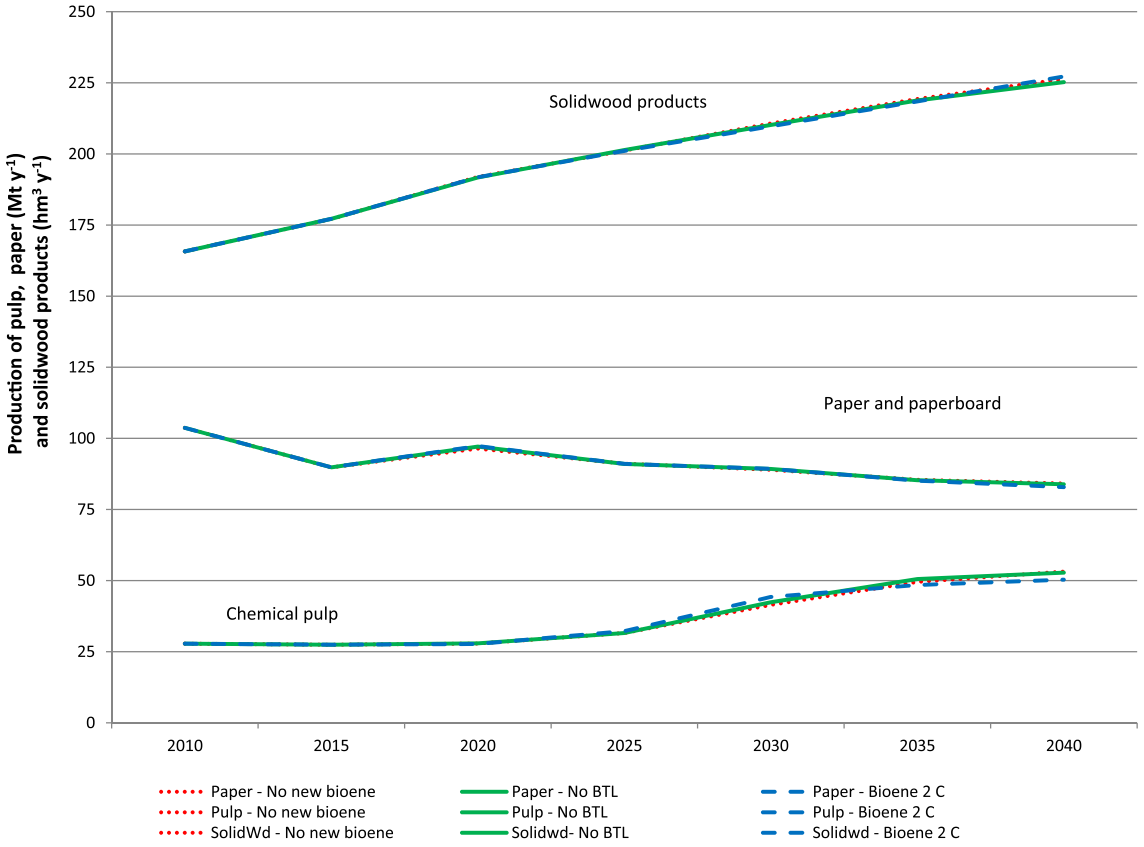

Fig. 3. Projected annual production of paper and chemical pulp (millions tonnes), and solid wood products (millions cubic metres) in the EEA when (i) bioenergy demand stays at 2010 level ("No new bioene"), (ii) wood use increases in heat and power production but no wood based biofuels enter the market ("No BTL"), and (iii) all bioenergy increases contributing to limit climatic warming to 2 °C ("Bioene 2 C").

projections. The required investments into the production capacity would be large to take place in a decade or two. Delays in realizing the investments from the planning phase up to market operation and the uncertainties faced by the investors regarding future policies and the price and availability of biomass are considerable. Hence, the investors may go into large projects sequentially in order to see how the previous investments are being met in the market, and this process can be slow.

4. Conclusions

If wood-based heat, power and biofuels production are increased in order to respond to the goal of keeping the climatic warming below 2 °C, the production of bioenergy will increase globally. Our results indicate that under such setting the European forest industry production would not be affected much by increased competition for biomass, because the rivalling regions face similar biomass demand challenges. This and the relatively abundant biomass resources may help the European forest industry to maintain its market shares.

Our results suggests also that feedstock costs and prices of biofuels can have drastic impacts on the allocation of biomass use between the production of heat, power and liquid biofuels in Europe. Because these economic factors are affected by policies, the policy makers should have very clear goal settings for their preferred ways of solving the shift from fossil fuel based energy system to the system with less greenhouse gas emissions. The policies interfering with the markets should be designed so that biomass can be expected to go to the end uses providing the desired societal benefits. This means the challenge of setting the priorities between production of heat, power and fuels for alternative transport modes, also accounting for the other uses of wood and forests and environmental concerns.

In the short or medium term, when the production capacity of liquid biofuels is gradually accumulating, there is wood for both heat and power production and liquid biofuels. In the long run, the competition between them is projected to be more tight, and then the allocation of the use of biomass depends largely on the policies. Yet, because the investments for biorefinery capacities and the infrastructure are not taking place immediately and because in various parts of Europe the biomass availability is not yet of strong concern in the next decade, there remains room for the policy makers to adjust taxes, support mechanisms and restrictions governing the biofuel use in order to control the development.

Nevertheless, early assessment of the future biomass availability and decisions based on that are needed, because the investments in biorefineries, heat and power plants or forest industry production facilities are irreversible and shape the market demand for wood biomass for a long time. Particularly, the new heat and power plants can be rather flexible in their fuel use. Hence, in the regions where there is no cap for GHG emissions for the heat and power plants or where these plants can source the emission allowances from the market, the plants that are flexible in their fuel choices can switch to fossil fuels if biomass is not available at competitive prices. Such a situation with severe competition over biomass would not be good for climate or for the society that possibly have subsidized building these heat and power plants or biofuel plants.

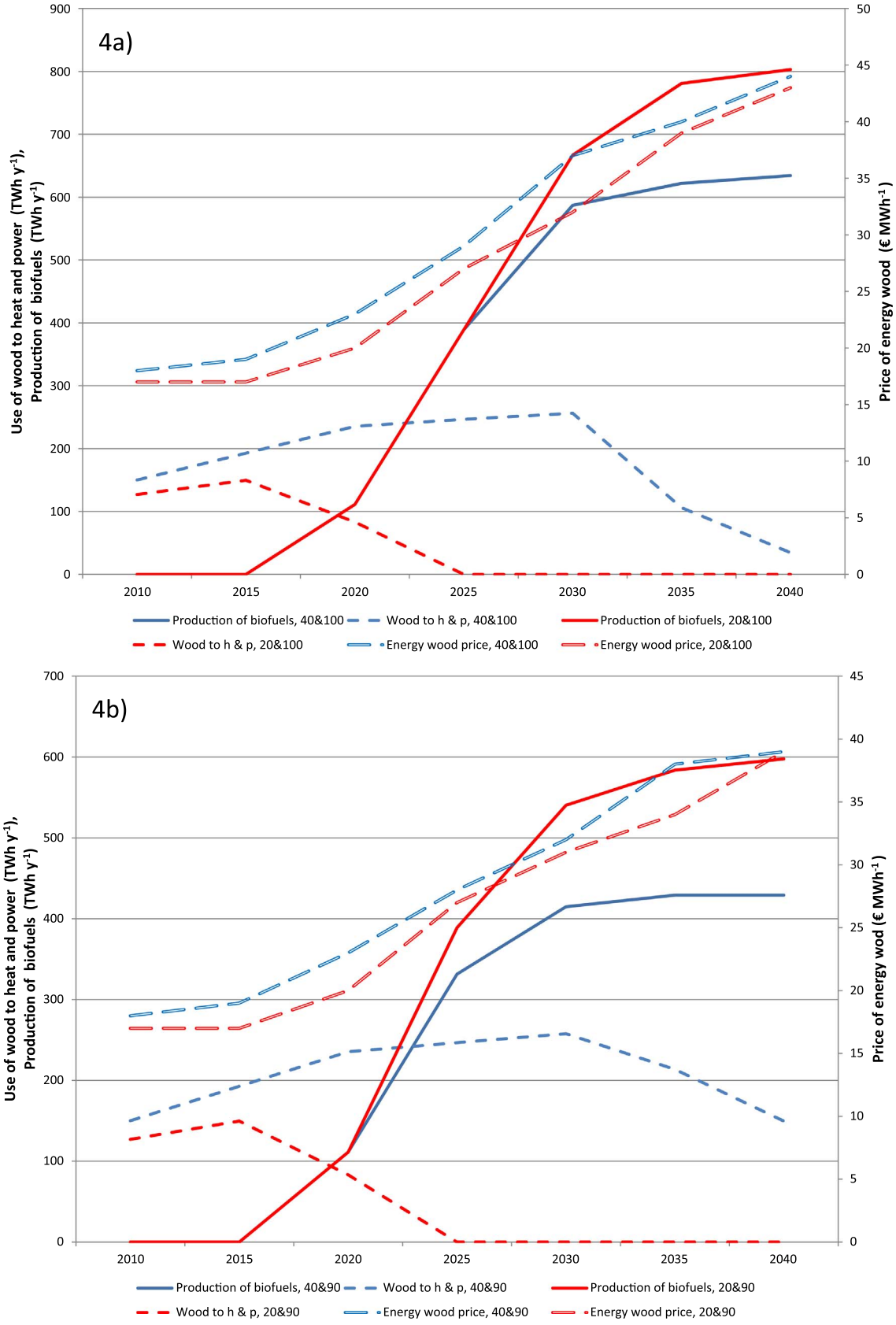
4a)
Use of wood to heat and power (TWh y-1), Production of biofuels (TWh y-1)
Price of energy wood (€ MWh-1)
Production of biofuels, 40&100
Wood to h & p, 40&100
Production of biofuels, 20&100
Wood to h & p, 20&100
Energy wood price, 40&100
Energy wood price, 20&100
4b)
Use of wood to heat and power (TWh y-1), Production of biofuels (TWh y-1)
Price of energy wod (€ MWh-1)
Production of biofuels, 40&90
Wood to h & p, 40&90
Production of biofuels, 20&90
Wood to h & p, 20&90
Energy wood price, 40&90
Energy wood price, 20&90

Fig. 4. a–d. Projected use of wood in heat and power production (TWh y^{-1}), production of wood-based liquid bi–ofuels (TWh y^{-1}), and market equilibrium price for energy wood (€·MWh^{-1}) in the EEA, when the heat and power plants can pay at maximum 20 €·MWh^{-1} (red) or 40 €·MWh^{-1} (blue) for wood and when the liquid biofuel price at mill gate is 100 €·MWh^{-1} (4a), 90 €/MWh (4b), 80 €·MWh^{-1} (4c) or 70 €·MWh^{-1} (4d). For instance 20&100 refers to the respective price combination of 20 €·MWh^{-1} and 100 €·MWh^{-1}. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

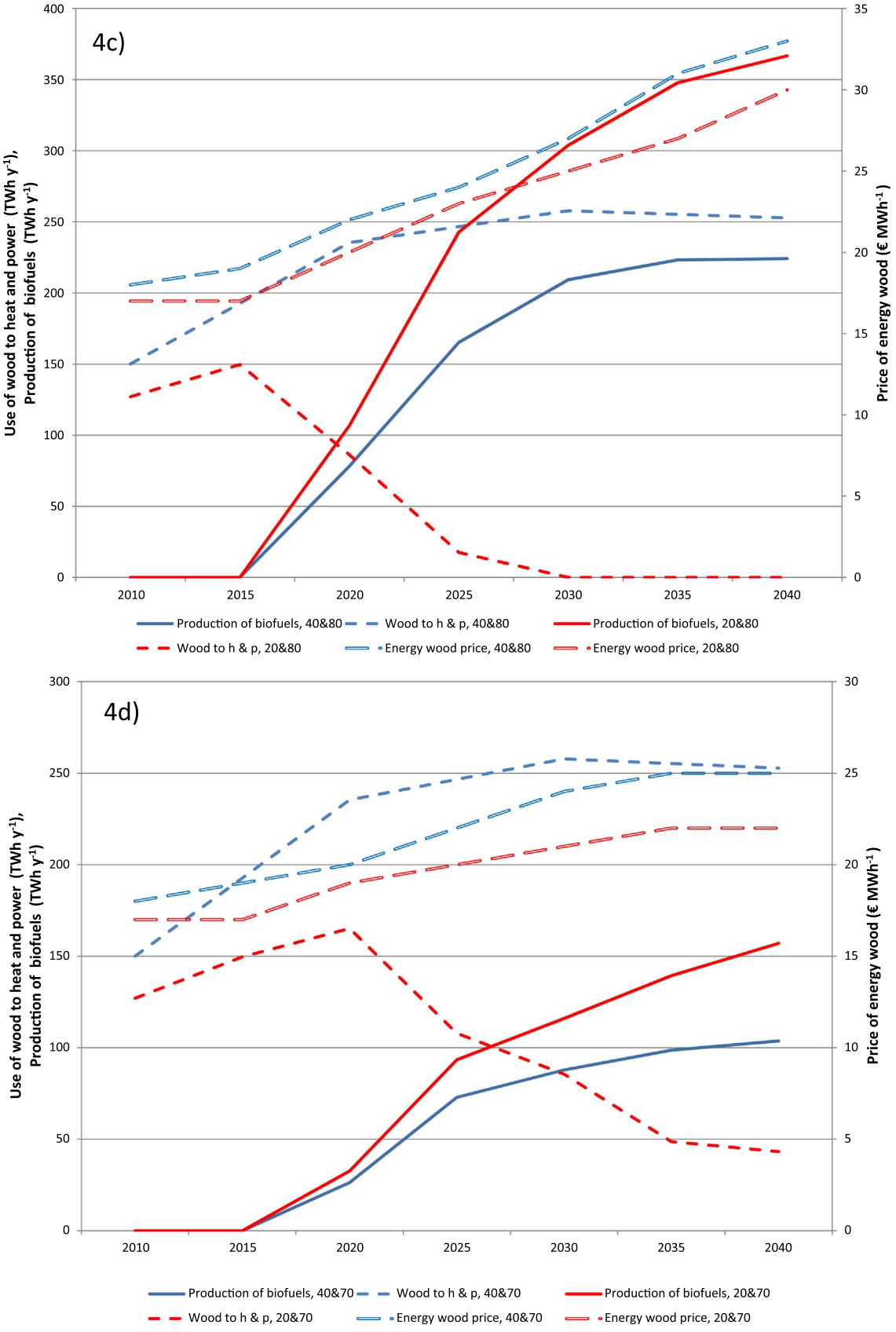
4c)
Use of wood to heat and power (TWh y-1), Production of biofuels (TWh y-1)
Price of energy wood (€ MWh-1)
Production of biofuels, 40&80
Wood to h & p, 40&80
Production of biofuels, 20&80
Wood to h & p, 20&80
Energy wood price, 40&80
Energy wood price, 20&80
4d)
Use of wood to heat and power (TWh y-1), Production of biofuels (TWh y-1)
Price of energy wood (€ MWh-1)
Production of biofuels, 40&70
Wood to h & p, 40&70
Production of biofuels, 20&70
Wood to h & p, 20&70
Energy wood price, 40&70
Energy wood price, 20&70

Fig. 4. (*continued*)

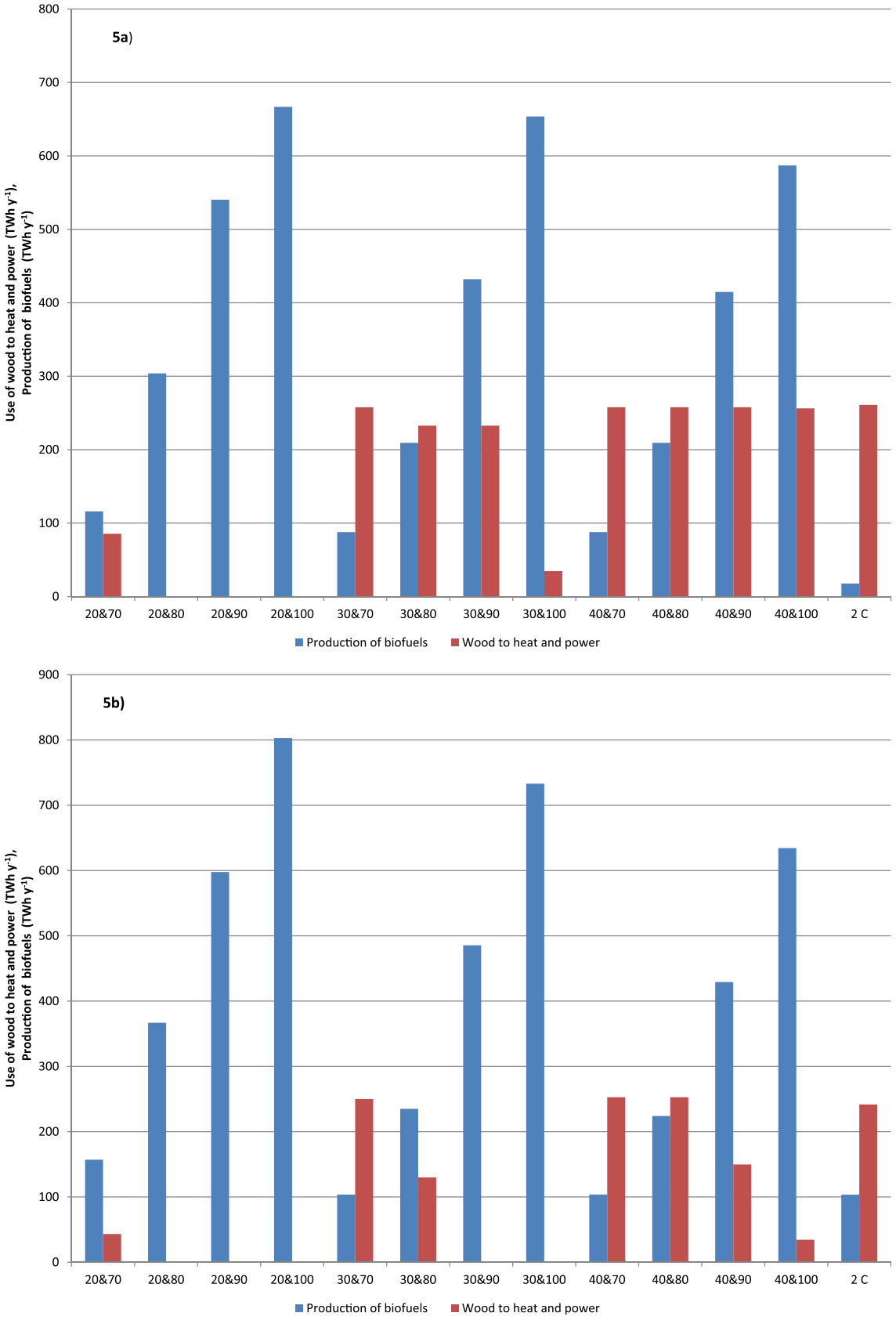

Fig. 5. a–b. Projected production of wood based liquid biofuels (TWh y^{-1}) and use of wood in heat and power plants (TWh y^{-1}) in the EEA in 2030 (5a) and 2040 (5b) with alternative combinations of prices that heat and power plants can pay for wood at maximum (€·MWh^{-1}) and the price of liquid biofuel at mill gate (€·MWh^{-1}). For instance 20&100 refers to the respective price combination of 20 €·MWh^{-1} and 100 €·MWh^{-1}, and "2 C" refers to quantities projected to be needed for 2 °C climate goal in Ref. [15].

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Appendix 1

The EFI-GTM model structure

The model structure is briefly presented below by introducing first the market agents and then the model. In the notations, the index referring to time t (year) is omitted for notational convenience, as the model is solved recursively, year after another. For more details regarding the functional forms and their specifications, we refer to [13].

Consumers

The consumers of the final forest industry products and biofuels, and heat and power plants buying wood for feedstock are represented in the model by inverse demand functions. Consumers are assumed to maximize their welfare, which is at greatest when consumers' surplus, defined as the area below the demand curve and above the market price is maximized for each product. In region i, let $q^i = (q_k^i)$ be a vector of the consumed quantities and let $P_k^i(q_k)$ be differentiable and non-increasing inverse demand function for product k. Let $\pi^i = (\pi_k^i)$ be a vector of product prices that consumers take as given, and let Q^i denote the closed, convex, and non-empty consumption possibility set.

Producers

Producers (e.g., timber growers, forest industry firms, biofuel producers) of a given region i maximize their profits, which can be defined as producer's surplus. Let $z^i = (z_k^i)$ be a vector of net output volumes for products k in region i, and let $C_k^i(z_k)$ be the marginal cost function for product k. The production possibility set V^i is assumed to a closed, convex, and non-empty. For the forest industry and biofuel producers, production with each production technology in region i is limited by a periodic capacity. Some production technologies (available capacity using certain technology) are already in use and therefore for them the capital costs related to investment made previously are sunk. For new production capacity (investments), full capital costs are included into marginal costs$C_k^i(z_k)$, but these costs are removed if the investment has been profitable and thus realized in the previous period. As discussed (Table 1), we also imposed scenario dependent constraints for the regional heat, power and biofuels production levels. Under competitive markets, the producers take product prices π_k^i as given.

Trade

Trade can be illustrated like a separable activity carried out by trade agents. To maximize the gain from trade, exporters buy goods at the domestic price, pay for the transportation, and sell at the price of the importing region. Similarly, importers buy at import prices and aim to make profits by selling at the domestic prices. Notation e_k^{ij} refers to the exports for product k from region i to j, whereasD_k^{ij} denotes the transportation cost for a unit of product k from region i to j. Bilateral export flowe_k^{ij} of a product matches the import flowe_k^{ji}.

Market equilibrium

For the markets to be equilibrium it must hold for every endogenous commodity and all regions that the consumption plus imports is equal to production and exports. Furthermore, all the agents (producers, consumers and traders) must be in their optimal solution given the market equilibrium prices and their own choice of production, consumption or trade quantities.

Model formulation

The profit or welfare maximization problems of the above agents are separable as all the agents are price takers. These problems can be aggregated and adding the condition that the market clears, the problem can be casted to one single convex optimization problem. There the competitive equilibrium is solved by maximizing sum of producers' and consumers' surpluses minus the transportation costs (Eq. (1)), subject to material balances (Eq. (2)), and constraints limiting production possibilities (mainly production capacities) (Eq. (3)) and constraints limiting consumption (Eq. (4)) and non-negativities related to activity variables (Eq. (5)) in all the regions.

$$Max_{q^i,z^i,e^{ij}} \quad \sum_{ik}\left[\int_o^{q_k^i} P_k^i(q_k^i)\mathrm{d}q_k^i - \int_o^{zi_k} C_k^i(z_k^i)dz_k^i\right] - \sum_{ijk} D_k^{ij} e_k^{ij} \tag{1}$$

$$q_k^i + \sum_j e_k^{ij} = z_k^i + \sum_j e_k^{ji}, \qquad \forall\, ki. \tag{2}$$

$$z^i \in V^i \quad \forall\, i. \tag{3}$$

$$q^i \in Q^i \quad \forall\, i. \tag{4}$$

$$q^i, x^i, e^{ij} \geq 0 \quad \forall\, ij. \tag{5}$$

The optimality conditions for the problem above equal the equilibrium conditions for regional competitive markets for one period t. The dynamic changes from year to year are modelled by recursive programming. That is, the long run spatial market equilibrium problem is broken up into a

sequence of short run problems, one for each year. Hence, the decision makers in the economy are assumed to have imperfect foresight.

After each period, the data on market demand, timber supply and changes in production costs and available technologies and their capacities are updated. Between the periods, it is possible to introduce assumptions regarding for instance demand growth or exogenous input prices that may be assumed to change in the future. Thereafter, a new equilibrium is computed subject to the new demand and supply conditions, new technologies, and new capacities.

Appendix 2

Table A.1
Biofuel technologies specified into the model based on studies [7,24–26].

Input per 1 MWh of biofuel output (negative figure is by-product)	FT-Liquid fuels Tehc. integrated to pulp mill, adapted from Ref. [24]	FT-Liquid fuels Tech. LTFT-3 in Ref. [25]	FT-Liquid fuels Tech. LTFT-2 in Ref. [25]	Gasoline Tech. SG in Refs. [7,26]	Gasoline Tech. OG in Refs. [7,26]	Gasoline Tech. SG+ in Refs. [7,26]	Gasoline Tech. OG+ in Refs. [7,26]
Biomass, MWh	1.05	1.75	1.91	1.96	1.93	1.02	0.75
Power, MWh	0.20	0.01	−0.01	0.047	0.079	1.020	1.316
Heat, GJ	0	−1.0	−1.30	−1.47	−1.33	−1.21	−1.22
Other o&m costs, €	14.0	10.9	11.9	21.3	21.5	12.1	9.7
Capital costs, €	35	32.1	35.2	65.4	66.4	37.5	29.8

Notes: Tech. refers to technology. FT refers to Fischer-Tropsch. Possible output of LPG (Liquefied Petroleum Gas) is aggregated to heat output in gasoline technologies. SG and OG refer to steam and oxygen gasification, respectively. O&m refer to operation and management. In hydrogen boosted technologies (marked with +), electricity includes power needed for producing hydrogen. Wood biomass is measured wet with 50% water content.

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